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A new mechanism for the generation of quasi-zonal jets in the ocean

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[1] A simple barotropic quasi-geostrophic model is used to demonstrate that instabilities radiated from an unstable eastern boundary current can generate zonal striations in the ocean interior with realistic wavelengths and amplitudes. Nonlinear transfer of energy from the more unstable trapped modes is important for radiating modes to overcome friction. The dynamics shown here are generic enough to point to the eastern boundary current as a likely source of the observed striations extending from oceanic eastern boundaries.
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1. Quasi-zonal Jets in the Ocean

[2] Quasi-zonal jet-like features have been directly measured in regional oceans [*Hogg and Owens*, 1999; *van Sebille et al.*, 2011], detected in global satellite altimetry data [*Maximenko et al.*, 2005], and simulated by high resolution numerical models [*Nakano and Hasumi*, 2005; *Richards et al.*, 2006; *Kamenkovich et al.*, 2009]. These quasi-zonal jet-like features are not universally accepted as real jets, and are often referred to as striations [e.g., *Maximenko et al.*, 2008]. They have a typical time-mean velocity scale of few centimeters per second, a meridional wavelength of about 200–600 km, a zonal extent of the basin scale, and highly coherent vertical structures. Figure 1a is a reproduction of Figure 2e in *Maximenko et al.* [2008] showing an example of the striations in the eastern part of the North Pacific subtropical gyre. While they have been the focus of much recent work, and the ubiquity of these striations is confirmed to be a robust feature in various data sets and numerical simulations, their formation and maintenance are still not fully understood. In this study, we propose and demonstrate a new mechanism which is largely unexplored by current literature: zonal striations in the ocean can be generated by nonlinear radiating instabilities of an unstable eastern boundary current (EBC).

2. The Mechanisms

[3] Several mechanisms have been proposed for the generation of zonal striations. One is attributed to anisotropic inverse energy cascade in beta-plane turbulence. By comparing the data of giant planets and a numerical simulation of North Pacific, *Galperin et al.* [2004] concluded that both striations in the ocean and zonal jets in the atmospheres of giant planets are governed by this anisotropic inverse cascade. The Rhines scale, at which nonlinear advection of the relative vorticity and linear advection of the planetary vorticity reach a balance [*Rhines*, 1975], is often used as a characteristic meridional scale of zonal jets in unforced beta-plane turbulence. Some numerical studies confirm that the meridional scale of the striations is consistent with the Rhines scale [*Nakano and Hasumi*, 2005; *Galperin et al.*, 2004; *Richards et al.*, 2006], but other studies based on observations [*Maximenko et al.*, 2008; *Melnichenko et al.*, 2010] or quasi-geostrophic multi-layer models [*Berloff et al.*, 2009] find that the striations in their studies are not related to the Rhines scale. However, the scaling of the jet spacing with the Rhines scale is not conclusive, and other parameters, such as external forcing or friction, may alter the scaling parameter. It is still unclear to what extent the quasi-zonal striations found in the ocean are generated by the zonation of beta-plane turbulence.

[4] Striations can also be formed from the trace of westward propagating eddies, which can be randomly distributed eddies [*Schlax and Chelton*, 2008] or eddies following preferred pathways [*Maximenko et al.*, 2008; *Scott et al.*, 2008]. However, *Melnichenko et al.* [2010] use observations and an eddy resolving model to show that eddies interact with striations suggesting that at least some striations may not be an artifact of time-averaging of westward propagating eddies.

[5] Other generation mechanisms are related to radiating linear and nonlinear waves from EBCs, which have long been observed [*Wooster and Reid*, 1963]. Based on observations, *Maximenko et al.* [2008] specifically discussed the striations over two subtropical eastern boundary regions, and showed that robust striations extend to or from eastern boundaries (Figure 1a). *Centurioni et al.* [2008] also found that four permanent meanders in the California Current System are connected to long bands of quasi-zonal flows in the interior of the Pacific ocean. Based on a linear stability analysis, *Hristova et al.* [2008] showed that the structures of the radiating instabilities from an unstable EBC predicted by linear theory are similar to the zonal striations in the ocean, and suggested that radiating instability can be one of the causes of the striations. A similar mechanism is demonstrated in a rotating tank experiment by *Afanasyev et al.* [2011], who showed that perturbations by buoyancy fluxes at an eastern boundary propagate westward as baroclinic Rossby waves to form so-called $\beta-$plumes, which then form interior zonal jets.

[6] The connection between interior striations and oceanic eastern boundaries is very clear in many studies [e.g., *Galperin*

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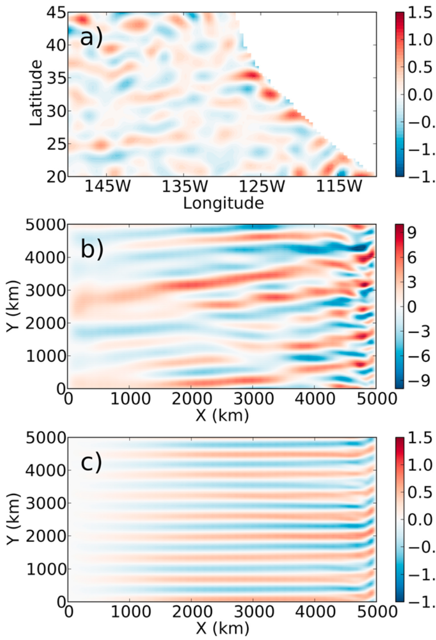

Figure 1. (a) A reproduction of Figure 2e in *Maximenko et al.* [2008] showing the high-pass filtered mean dynamic ocean topography (cm). The corresponding geostrophic zonal velocity has amplitude of 1 cm/s [*Melnichenko et al.*, 2010]. (b) A snapshot of the surface height anomaly in the model (cm). The anomaly is the deviation of surface height from its meridional mean. (c) The 10-year time average of the model surface height anomaly (cm).

et al., 2004, Figure 1b; *Nakano and Hasumi*, 2005, Figure 4; *Centurioni et al.*, 2008, Figure 5; *Maximenko et al.*, 2008, Figure 2]. The linear inviscid radiating instabilities in *Hristova et al.* [2008] show striations, however, the growth rate of the linear radiating mode is very small relative to the most unstable mode. Finite amplitude frictional damping may suppress the growth of the linear radiating modes, leaving the significance of the linear mode for generating quasi-zonal jets undetermined. In addition, nonlinear effects can be important, as assessed in *Melnichenko et al.* [2010]. In this letter, we extend the study by *Hristova et al.* [2008] using a nonlinear model to show that the nonlinear radiating instabilities of an eastern boundary current can produce reasonable zonal striations that resemble those in altimetry data. The underlying mechanism is only briefly discussed here, but is extensively discussed in *Wang* [2011].

3. Striations in a Simple Numerical Model

[7] This study uses a simple nonlinear numerical model described by the barotropic quasi-geostrophic vorticity equation [*Pedlosky*, 1987],

$$q_t + J(\psi, q + \beta y) = \frac{f_0}{D} w_E + \nabla \cdot A_h \nabla q, \qquad (1)$$

where $q = \nabla^2 \psi$ is the relative vorticity, ψ the streamfunction, f_0 the Coriolis parameter at a fixed latitude, β the northward gradient of the Coriolis parameter, $q + \beta y$ the barotropic potential vorticity, D the layer thickness, A_h lateral viscosity. A_h is strongly increased at the western boundary to damp signals there, since they are not our focus, and to parametrize high enstrophy dissipation [*Fox-Kemper*, 2003].

$$A_h = A_h^w - \left(A_h^w - A_h^e\right) \exp\left(\frac{x - L}{0.15L}\right), \qquad (2)$$

where L is the domain size, $x = 0$ is placed at the western boundary and $x = L$ at the eastern boundary. This function is controlled by A_h^w at the western side and is A_h^e at the eastern side.

[8] We force an unstable EBC by specifying an Ekman pumping w_E such that the mean boundary current is forced towards a given profile, which is denoted by $v(x)$ hereafter. For a specific $v(x)$, the forcing field w_E is calculated following $\frac{f}{D} w_E = \beta v(x) - \partial_x A_h \partial_{xx} v(x)$. The $v(x)$ is specified as

$$v = \operatorname{sech}\left(\frac{x - L + x_c}{L_b}\right)^2, \qquad (3)$$

where x_c and L_b represent the position and the width of the boundary current, respectively.

[9] The model is integrated for 30 years in a meridional channel that extends 5000 km in both the zonal and meridional directions. The following analysis is based on the last 10 years of the simulation. The boundary conditions are periodic in the meridional direction, with no-normal-flow and slip conditions along the eastern and western walls. The model grid is 256 × 256, giving a resolution of 19.53 km. This resolution is sufficient for the most unstable mode, which has a meridional wavelength of 357 km. The values of the parameters used in this study are: $\beta = 2 \times 10^{-11}$/ms, $\frac{f}{D} w_E = 4 \times 10^{-12}/\mathrm{s}^2$ corresponding to a boundary current $v \approx 0.2$ m/s, $A_h^w = 10^4 \mathrm{m}^2/\mathrm{s}$, $A_h^e = 100\ \mathrm{m}^2/\mathrm{s}$, $x_c = 100$ km, and L_b 50 km. The speed and the width of the boundary current are in the observed scale [*Hickey*, 1979; *Davis*, 1985; *Brink and Cowles*, 1991]. A descendant of the pseudospectral code used in *Flierl and Pedlosky* [2007] is implemented to solve equation (1).

[10] Interior zonal striations are clearly shown in a snapshot of the surface height anomaly (Figure 1b). The striations have small zonal but large meridional wavenumbers. The maximum anomaly exceeds 9 cm. The associated zonal

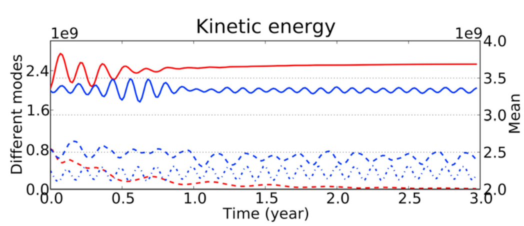

Figure 2. The evolution of the domain-integrated kinetic energy in two experiments initialized by the final state of the experiment shown in Figure 1. The model is truncated to only consist of two modes in the first experiment (red), the mean eastern boundary current (red solid) and LM (714 km wavelength) (red dashed). The model is truncated to retain three modes in the second experiment (blue), the mean (blue solid), LM (blue dashed), and SM (357 km wavelength) (blue dotted).

velocity (figure not shown) is about 10 cm/s. The striations are generated by radiating instabilities of the forced EBC as no forcing is applied in the interior.

[11] Nonlinear processes are important in generating the striations. A Fourier analysis of the streamfunction shows that the most energetic disturbances have a meridional wavelength 357 km (the shortwave mode, SM hereafter) in the EBC region and 714 km (the longwave mode, LM hereafter) in the interior. Based on a linear analysis of the prescribed EBC velocity profile, we know that the SM is the most unstable linear mode but is trapped around the EBC. LM is a radiating mode with a long tail extending into the interior but has a negative growth rate. Linearly decaying radiating modes, LM, can not generate persistent interior striations, and are sustained by interacting nonlinearly with SM.

[12] Two experiments are carried out to demonstrate the importance of nonlinear interactions in supporting the radiating instabilities. In the first experiment, the model is truncated to consist of two modes, the mean EBC and LM. The model in the second experiment is truncated to consist of three modes, the mean EBC, LM, and SM. Both experiments use the final state of the 30-year simulation as their initial conditions. Figure 2 shows that the domain-integrated kinetic energy of LM (red dashed) decays in the first experiment, but is sustained in the second experiment with the presence of SM. This is a simple demonstration that LM is not supported by the mean boundary current, but by SM. The energy transfer is done through triad-resonance.

[13] Triad-resonance occurs among a wave triad if the wavenumbers and frequencies of the triad satisfy $l_1 \pm l_2 \pm l_3 = 0$ and $\omega_1 \pm \omega_2 \pm \omega_3 = 0$, where l represents wavenumber and ω represents frequency [*Phillips*, 1960]. In our case, the criteria for triad-resonance is satisfied between LM and SM, as LM has a wavelength 714 km and a period 134 days, and SM 357 km and 67 days, equivalently $l_{SM} \pm 2l_{LM} = 0$ and $\omega_{SM} \pm 2\omega_{LM} = 0$. Here LM and SM are harmonics, but the energy redistribution occurs for more general wave triads. More details about dynamics of the triad-resonance can be found in *Wang* [2011].

[14] The westward-extending structure of the radiating instabilities is essentially caused by westward propagation of boundary perturbations. The zonal tilt of the striations means that unstable boundary perturbations generate westward propagating waves while they propagate northward, so that the wave crests/troughs emitted at later times lie to the north of those emitted at earlier times. As a result, the angle of the zonal tilt depends on the direction of the boundary current.

[15] Ideally, the meridionally uniform forcing in a meridionally periodic channel drives fields with a zero time average. The nonlinear interactions, however, generate strong temporal variations. The residue of a time average over a finite period can be large. Figure 1c shows the time average of the surface height anomaly over a 10 year period. The amplitude of the time-mean is still around 1.5 cm, which is similar to the results from observations averaged over a similar time period [*Maximenko et al.*, 2008; *Melnichenko et al.*, 2010]. The meridional wavelength in the model is also similar to that in the observations [*Maximenko et al.*, 2008]. The time-mean field shows pure zonal striations because the waves emitted from the eastern boundary propagate westward. The zonal tilt in the observations may be due to the large scale meridional flow of the wind driven gyre [*Maximenko and Niiler*, 2006].

4. Conclusion and Discussion

[16] Nonlinear simulations based on a simple numerical model demonstrate that the quasi-zonal striations reported in the literature can be generated by the radiating instabilities of an EBC, as suggested by the linear instability study by *Hristova et al.* [2008]. However, the nonlinear dynamics are important in the radiation mechanism, and our study shows that the radiating waves emerge in the presence of dissipation and nonlinearities to generate interior striations with realistic amplitudes. This could not have been anticipated from linear theory because the mechanism, as identified here, is intrinsically nonlinear. Now that we have identified this mechanism, one could predict the nonlinear radiation response from the linear theory.

[17] That finite amplitude of the striations in the time-mean field resulted from the residue of a strong temporal variation indicates that one should be cautious about interpreting the striations in observations to be stationary. However, this does not imply that the striations caused by radiating instability can not be stationary. It is well studied and accepted that the irregularity of the coastline and topography is very important for anchoring coastal filaments and for enhancing the growth of meanders and eddies [*Kelly*, 1985; *Batteen*, 1997; *Brink and Cowles*, 1991]. The permanent meanders are connected to quasi-zonal striations extending for several thousands of kilometers into the interior [*Centurioni et al.*, 2008]. It is unclear how irregular coastlines and bottom topography affect the radiating instabilities, but one can expect that the long-time average of radiating instabilities in the interior will have a finite amplitude because of the spatially irregular but stationary continental coasts. The time-mean field can then show traces of the long radiating modes emitted from EBCs.

[18] Since the simplest barotropic QG model can capture striations with wavelengths and amplitudes which resemble those observed in the satellite data, we anticipate similar features will occur in more complex systems. Although it is still unclear whether there is one universal mechanism that can explain striations observed throughout the world ocean, these results demonstrate that those close to the oceanic eastern boundary can be formed by radiating modes of the EBC which, in our case, overcome friction by nonlinear transfer of energy from the more unstable trapped modes. The dynamics shown here seems generic enough to point to the EBC as a major source.

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